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GREATEST LEAST EIGENVALUE OF THE LAPLACIAN ON THE KLEIN BOTTLE

AHMAD EL SOUFI, HECTOR GIACOMINI AND MUSTAPHA JAZAR

ABSTRACT. We prove the following conjecture recently formulated by Jakobson, Nadirashvili and Polterovich [12]: For any Riemannian metric g on the Klein bottle \mathbb{K} one has

$$\lambda_1(\mathbb{K}, g)A(\mathbb{K}, g) \leq 12\pi E(2\sqrt{2}/3),$$

where $\lambda_1(\mathbb{K}, g)$ and $A(\mathbb{K}, g)$ stand for the least positive eigenvalue of the Laplacian and the area of (\mathbb{K}, g) , respectively, and E is the complete elliptic integral of the second kind. Moreover, the equality is uniquely achieved, up to dilatations, by the metric

$$g_0 = \frac{9 + (1 + 8 \cos^2 v)^2}{1 + 8 \cos^2 v} \left(du^2 + \frac{dv^2}{1 + 8 \cos^2 v} \right),$$

with $0 \leq u, v < \pi$. The proof of this theorem leads us to study a Hamiltonian dynamical system which turns out to be completely integrable by quadratures.

1. INTRODUCTION AND STATEMENT OF MAIN RESULTS

Among all the possible Riemannian metrics on a compact differentiable manifold M , the most interesting ones are those which extremize a given Riemannian invariant. In particular, many recent works have been devoted to the metrics which maximize the fundamental eigenvalue $\lambda_1(M, g)$ of the Laplace-Beltrami operator Δ_g under various constraints (see, for instance, [4, 11, 13, 15, 16]). Notice that, since $\lambda_1(M, g)$ is not invariant under scaling ($\lambda_1(M, kg) = k^{-1}\lambda_1(M, g)$), such constraints are necessary.

In [19], Yang and Yau proved that, on any compact orientable surface M , the first eigenvalue $\lambda_1(M, g)$ is uniformly bounded over the set of Riemannian metrics of fixed area. More precisely, one has, for any Riemannian metric g on M ,

$$\lambda_1(M, g)A(M, g) \leq 8\pi(\text{genus}(M) + 1),$$

where $A(M, g)$ stands for the Riemannian area of (M, g) (see [7] for an improvement of the upper bound). In the non-orientable case, the following upper bound follows from Li and Yau's work [13]: $\lambda_1(M, g)A(M, g) \leq 24\pi(\text{genus}(M) + 1)$. On the other hand, if the dimension of M is greater than 2, then $\lambda_1(M, g)$ is never bounded above over the set of Riemannian metrics of fixed volume, see [5].

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Hence, one obtains a relevant topological invariant of surfaces by setting, for any compact 2-dimensional manifold M ,

$$\Lambda(M) = \sup_g \lambda_1(M, g)A(M, g) = \sup_{g \in \mathcal{R}(M)} \lambda_1(M, g),$$

where $\mathcal{R}(M)$ denotes the set of Riemannian metrics of area 1 on M . The natural questions related to this invariant are :

- (1) How does $\Lambda(M)$ depend on (the genus of) M ?
- (2) Can one determine $\Lambda(M)$ for some M ?
- (3) Is the supremum $\Lambda(M)$ achieved, and, if so, by what metrics?

Concerning the first question, it follows from [6] that $\Lambda(M)$ is an increasing function of the genus with a linear growth rate. Explicit answers to questions (2) and (3) are only known for the three following surfaces : the sphere \mathbb{S}^2 , the real projective plane $\mathbb{R}P^2$ and the Torus \mathbb{T}^2 . Indeed, according to the results of Hersch [11], Li and Yau [13] and Nadirashvili [15], one has

$$\Lambda(\mathbb{S}^2) = \lambda_1(\mathbb{S}^2, g_{\mathbb{S}^2})A(\mathbb{S}^2, g_{\mathbb{S}^2}) = 8\pi,$$

where $g_{\mathbb{S}^2}$ is the standard metric of \mathbb{S}^2 (see [11]),

$$\Lambda(\mathbb{R}P^2) = \lambda_1(\mathbb{R}P^2, g_{\mathbb{R}P^2})A(\mathbb{R}P^2, g_{\mathbb{R}P^2}) = 12\pi,$$

where $g_{\mathbb{R}P^2}$ is the standard metric of $\mathbb{R}P^2$ (see [13]), and

$$\Lambda(\mathbb{T}^2) = \lambda_1(\mathbb{T}^2, g_{eq})A(\mathbb{T}^2, g_{eq}) = \frac{8\pi^2}{\sqrt{3}},$$

where g_{eq} is the flat metric on $\mathbb{T}^2 \simeq \mathbb{R}^2/\Gamma_{eq}$ corresponding to the equilateral lattice $\Gamma_{eq} = \mathbb{Z}(1, 0) \oplus \mathbb{Z}(\frac{1}{2}, \frac{\sqrt{3}}{2})$ (see [15]). Moreover, on each one of these three surfaces, the maximizing metric is unique, up to a dilatation.

What about the Klein bottle \mathbb{K} ?

Nadirashvili [15] proved that the supremum $\Lambda(\mathbb{K})$ is necessarily achieved by a regular (real analytic) Riemannian metric. Recently, Jakobson, Nadirashvili and Polterovich [12] conjectured that the exact value of $\Lambda(\mathbb{K})$ is given by

$$\Lambda(\mathbb{K}) = 12\pi E(2\sqrt{2}/3) \simeq 13.365\pi,$$

where $E(2\sqrt{2}/3)$ is the complete elliptic integral of the second kind evaluated at $\frac{2\sqrt{2}}{3}$. They also conjectured that this value is uniquely achieved, up to a dilatation, by the metric of revolution

$$g_0 = \frac{9 + (1 + 8 \cos^2 v)^2}{1 + 8 \cos^2 v} \left(du^2 + \frac{dv^2}{1 + 8 \cos^2 v} \right),$$

with $0 \leq u, v < \pi$.

The main purpose of this paper is to prove this conjecture. Indeed, we will prove the following

Theorem 1.1. *For any Riemannian metric g on \mathbb{K} one has*

$$\lambda_1(\mathbb{K}, g)A(\mathbb{K}, g) \leq \lambda_1(\mathbb{K}, g_0)A(\mathbb{K}, g_0) = 12\pi E(2\sqrt{2}/3).$$

Moreover, the equality holds for a metric g if, and only if, g is homothetic to g_0 .

As noticed in [12], if we denote by $(\mathbb{T}^2, \bar{g}_0)$ the double cover of (\mathbb{K}, g_0) , then \bar{g}_0 is nothing but the Riemannian metric induced on \mathbb{T}^2 from the bipolar surface of Lawson's minimal torus $\tau_{3,1}$ defined as the image in \mathbb{S}^3 of the map

$$(u, v) \mapsto (\cos v \exp(3iu), \sin v \exp(iu)).$$

It is worth noticing that the metric g_0 does not maximize the systole functional $g \mapsto \text{sys}(g)$ (where $\text{sys}(g)$ denotes the length of the shortest non-contractible loop) over the set of metrics of fixed area on the Klein bottle (see [3]), while on $\mathbb{R}P^2$ and \mathbb{T}^2 , the functionals λ_1 and sys are maximized by the same Riemannian metrics.

The proof of Theorem 1.1 relies on the characterization of critical metrics of the functional λ_1 in terms of minimal immersions into spheres by the first eigenfunctions. Note that, in spite of the non-differentiability of this functional with respect to metric deformations, a natural notion of criticality can be introduced (see [9]). Moreover, the criticality of a metric g for λ_1 with respect to area preserving deformations is characterized by the existence of a family h_1, \dots, h_d of first eigenfunctions of Δ_g satisfying $\sum_{i \leq d} dh_i \otimes dh_i = g$. This last condition actually means that the map (h_1, \dots, h_d) is an isometric immersion from (M, g) into \mathbb{R}^d whose image is a minimal immersed submanifold of a sphere. Theorem 1.1 then follows from Nadirashvili's existence result and the following

Theorem 1.2. *The Riemannian metric g_0 is, up to a dilatation, the only critical metric of the functional λ_1 under area preserving deformations of metrics on \mathbb{K} .*

Equivalently, the metric g_0 is, up to a dilatation, the only metric on \mathbb{K} such that (\mathbb{K}, g_0) admits a minimal isometric immersion into a sphere by its first eigenfunctions.

In [8], Ilias and the first author gave a necessary condition of symmetry for a Riemannian metric to admit isometric immersions into spheres by the first eigenfunctions. On the Klein bottle, this condition amounts to the invariance of the metric under the natural \mathbb{S}^1 -action on \mathbb{K} . Taking into account this symmetry property and the fact that any metric g is conformally equivalent to a flat one, for which the eigenvalues and the eigenfunctions of the Laplacian are explicitly known, it is of course expected that the existence problem of minimal isometric immersions into spheres by the first eigenfunctions reduces to a second order system of ODEs (see Proposition 2.1). Actually, the substantial part of this paper is devoted to the study of the following second order nonlinear system:

$$(1) \quad \begin{cases} \varphi_1'' = (1 - 2\varphi_1^2 - 8\varphi_2^2)\varphi_1, \\ \varphi_2'' = (4 - 2\varphi_1^2 - 8\varphi_2^2)\varphi_2, \end{cases}$$

for which we look for periodic solutions satisfying

$$(2) \quad \begin{cases} \varphi_1 \text{ is odd and has exactly two zeros in a period,} \\ \varphi_2 \text{ is even and positive everywhere;} \end{cases}$$

and the initial conditions

$$(3) \quad \begin{cases} \varphi_1(0) = \varphi_2'(0) = 0 \text{ (from parity conditions),} \\ \varphi_2(0) = \frac{1}{2}\varphi_1'(0) =: p \in (0, 1]. \end{cases}$$

In [12], Jakobson, Nadirashvili and Polterovich proved that the initial value $p = \varphi_2(0) = \sqrt{3/8}$ corresponds to a periodic solution of (1)-(3) satisfying (2). Based on numerical evidence, they conjectured that this value of p is the only one corresponding to a periodic solution satisfying (2). As mentioned by them, a computer-assisted proof of this conjecture is extremely difficult, due to the lack of stability of the system.

In Section 3, we provide a complete analytic study of System (1). First, we show that this system admits two independent first integrals (one of them has been already found in [12]). Using a suitable linear change of variables, we show that the system becomes Hamiltonian and, hence, integrable. The general theory of integrable Hamiltonian systems tells us that bounded orbits correspond to periodic or quasi-periodic solutions (see [2]). However, to distinguish periodic solutions from non-periodic ones is not easy in general. Fortunately, our first integrals turn out to be quadratic in the momenta, which enables us to apply the classical Bertrand-Darboux-Whittaker Theorem and, therefore, to completely decouple the system by means of a parabolic type change of coordinates $(\varphi_1, \varphi_2) \mapsto (u, v)$. We show that, for any $p \neq \sqrt{3}/2$, the solutions u and v of the decoupled system are periodic. The couple (u, v) is then periodic if and only if the periods of u and v are commensurable. We express the periods of u and v in terms of hyper-elliptic integrals and study their ratio as a function of p . The following fact (Proposition 3.1) gives an idea about the complexity of the situation: there exists a countable dense subset $\mathcal{P} \subset (0, \sqrt{3}/2)$ such that the solution of (1)-(3) corresponding to $p \in (0, \sqrt{3}/2)$ is periodic if and only if $p \in \mathcal{P}$.

In conclusion, we show that the solution associated with $p = \sqrt{3/8}$ is the only periodic one to satisfy Condition (2).

2. PRELIMINARIES: REDUCTION OF THE PROBLEM

Let us first recall that, if g_ε is a smooth deformation of a metric g on a compact surface M , then the function $\varepsilon \mapsto \lambda_1(M, g_\varepsilon)$, which is continuous but not necessarily differentiable at $\varepsilon = 0$, always admits left and right derivatives at $\varepsilon = 0$ with

$$\frac{d}{d\varepsilon} \lambda_1(M, g_\varepsilon) \Big|_{\varepsilon=0^+} \leq \frac{d}{d\varepsilon} \lambda_1(M, g_\varepsilon) \Big|_{\varepsilon=0^-}$$

(see [9, 10] for details). The metric g is then said to be critical for the functional λ_1 under area preserving deformations if, for any deformation g_ε with $g_0 = g$ and $A(M, g_\varepsilon) = A(M, g)$, one has

$$\frac{d}{d\varepsilon} \lambda_1(M, g_\varepsilon) \Big|_{\varepsilon=0^+} \leq 0 \leq \frac{d}{d\varepsilon} \lambda_1(M, g_\varepsilon) \Big|_{\varepsilon=0^-}.$$

It is easy to check that this last condition is equivalent to:

$$\lambda_1(M, g_\varepsilon) \leq \lambda_1(M, g) + o(\varepsilon) \text{ as } \varepsilon \rightarrow 0.$$

Of course, the metric g is critical for the functional λ_1 under area preserving deformations if, and only if, it is critical for the functional $\lambda_1 \cdot A$.

Following [9] and [15], a necessary and sufficient condition for the metric g to be critical for λ_1 under area-preserving metric deformations is that there exists a family h_1, \dots, h_d of first eigenfunctions of Δ_g satisfying

$$(4) \quad \sum_{i \leq d} dh_i \otimes dh_i = g,$$

which means that the map $h = (h_1, \dots, h_d)$ is an isometric immersion from (M, g) to \mathbb{R}^d . Since h_1, \dots, h_d are eigenfunctions of Δ_g , the image of h is a minimal immersed submanifold of the Euclidean sphere $\mathbb{S}^{d-1} \left(\sqrt{\frac{2}{\lambda_1(M, g)}} \right)$ of radius $\sqrt{2/\lambda_1(M, g)}$ (Takahashi's theorem [17]). In particular, we have

$$(5) \quad \sum_{i \leq d} h_i^2 = \frac{2}{\lambda_1(M, g)}.$$

In [8], Ilias and the first author have studied conformal properties of Riemannian manifolds (M, g) admitting such minimal isometric immersions into spheres. It follows from their results that, if g is a critical metric of λ_1 under area preserving deformations, then

- (i) g is, up to a dilatation, the unique critical metric in its conformal class,
- (ii) g maximizes the restriction of λ_1 to the set of metrics conformal to g and having the same volume,
- (iii) the isometry group of (M, g) contains the isometry groups of all the metrics g' conformal to g .

For any positive real number a , we denote by Γ_a the rectangular lattice of \mathbb{R}^2 generated by the vectors $(2\pi, 0)$ and $(0, a)$ and by \tilde{g}_a the flat Riemannian metric of the torus $\mathbb{T}_a^2 \simeq \mathbb{R}^2/\Gamma_a$ associated with the rectangular lattice Γ_a . The Klein bottle \mathbb{K} is then diffeomorphic to the quotient of \mathbb{T}_a^2 by the involution $s : (x, y) \mapsto (x + \pi, -y)$. We denote by g_a the flat metric induced on \mathbb{K} by such a diffeomorphism. It is well known that any Riemannian metric on \mathbb{K} is conformally equivalent to one of the flat metrics g_a .

Let $g = fg_a$ be a Riemannian metric on \mathbb{K} . From the property (iii) above, if g is a critical metric of λ_1 under area preserving deformations, then $\text{Isom}(\mathbb{K}, g_a) \subset \text{Isom}(\mathbb{K}, g)$, which implies that the function f is invariant under the \mathbb{S}^1 -action $(x, y) \mapsto (x + t, y)$, $t \in [0, \pi]$, on \mathbb{K} , and then, f (or its lift to \mathbb{R}^2) does not depend on the variable x .

Proposition 2.1. *Let a be a positive real number and f a positive periodic function of period a . The following assertions are equivalent*

- (I) *The Riemannian metric $g = f(y)g_a$ on \mathbb{K} is a critical metric of λ_1 under area preserving deformations.*
- (II) *The function f is proportional to $\varphi_1^2 + 4\varphi_2^2$, where φ_1 and φ_2 are two periodic functions of period a satisfying the following conditions:*

(a) (φ_1, φ_2) is a solution of the equations

$$\begin{cases} \varphi_1'' = (1 - 2\varphi_1^2 - 8\varphi_2^2)\varphi_1, \\ \varphi_2'' = (4 - 2\varphi_1^2 - 8\varphi_2^2)\varphi_2; \end{cases}$$

(b) φ_1 is odd, φ_2 is even and $\varphi_1'(0) = 2\varphi_2(0)$;

(c) φ_1 admits two zeros in a period and φ_2 is positive everywhere;

(d) $\varphi_1^2 + \varphi_2^2 \leq 1$ and the equality holds at exactly two points in a period.

Most of the arguments of the proof of “(I) implies (II)” can be found in [12]. For the sake of completeness, we will recall the main steps. The proof of the converse relies on the fact that the system (1) admits two independent first integrals.

Proof. The Laplacian Δ_g associated with the Riemannian metric $g = f(y)g_a$ on \mathbb{K} can be identified with the operator $-\frac{1}{f(y)}(\partial_x^2 + \partial_y^2)$ acting on Γ_a -periodic and s -invariant functions on \mathbb{R}^2 . Using separation of variables and Fourier expansions, one can easily show that any eigenfunction of Δ_g is a linear combination of functions of the form $\varphi_k(y) \cos kx$ and $\varphi_k(y) \sin kx$, where, $\forall k$, φ_k is a periodic function with period a satisfying $\varphi_k(-y) = (-1)^k \varphi_k(y)$ and $\varphi_k'' = (k^2 - \lambda f)\varphi_k$. Since a first eigenfunction always admits exactly two nodal domains, the first eigenspace of Δ_g is spanned by

$$\{\varphi_0(y), \varphi_1(y) \cos x, \varphi_1(y) \sin x, \varphi_2(y) \cos 2x, \varphi_2(y) \sin 2x\},$$

where, unless they are identically zero, φ_2 does not vanish while φ_0 and φ_1 admit exactly two zeros in $[0, a)$. In particular, the multiplicity of $\lambda_1(\mathbb{K}, g)$ is at most 5.

Let us suppose that g is a critical metric of λ_1 under area preserving deformations and let h_1, \dots, h_d be a family of first eigenfunctions satisfying the equations (4) and (5) above. Without loss of generality, we may assume that $\lambda_1(\mathbb{K}, g) = 2$ and that h_1, \dots, h_d are linearly independent, which implies that $d \leq 5$. Since $h = (h_1, \dots, h_d) : \mathbb{K} \rightarrow \mathbb{S}^{d-1}$ is an immersion, one has $d \geq 4$. If $d = 4$, then using elementary algebraic arguments like in the proof of Proposition 5 of [14], one can see that there exists an isometry $\rho \in O(4)$ such that $\rho \circ h = (\varphi_1(y)e^{ix}, \varphi_2(y)e^{2ix})$ with $\varphi_1^2 + \varphi_2^2 = 1$ (eq. (5)) and $\varphi_1'^2 + \varphi_2'^2 = \varphi_1^2 + 4\varphi_2^2 = f$ (eq. (4)) which is impossible since $\varphi_1^2 + \varphi_2^2 = 1$ implies that φ_1 and φ_2 admit a common critical point. Therefore, $d = 5$ and there exists $\rho \in O(5)$ such that $\rho \circ h = (\varphi_0(y), \varphi_1(y)e^{ix}, \varphi_2(y)e^{2ix})$, with $\varphi_0^2 + \varphi_1^2 + \varphi_2^2 = 1$ and $\varphi_0'^2 + \varphi_1'^2 + \varphi_2'^2 = \varphi_1^2 + 4\varphi_2^2 = f$. Since the linear components of $\rho \circ h$ are first eigenfunctions of (\mathbb{K}, g) , one should have, $\forall k = 0, 1, 2$, $\varphi_k'' = (k^2 - \lambda_1(\mathbb{K}, g)f)\varphi_k = (k^2 - 2\varphi_1^2 - 8\varphi_2^2)\varphi_k$. Now, it is immediate to check that one of the couples of functions $(\pm\varphi_1, \pm\varphi_2)$ satisfies the Conditions (a), \dots , (d) of the statement. Indeed, the parity condition $\varphi_k(-y) = (-1)^k \varphi_k(y)$ implies that $\varphi_1(0) = \varphi_0'(0) = \varphi_1'(0) = 0$ and, then, $\varphi_1''(0) = 4\varphi_2^2(0)$. Conditions (c) and (d) follow from the fact that a first eigenfunction has exactly two nodal domains in \mathbb{K} .

Conversely, let φ_1 and φ_2 be two periodic functions of period a satisfying Conditions (a), \dots , (d) and let us show that the metric $g = f(y)g_a$, where

$f = \varphi_1^2 + 4\varphi_2^2$, is a critical metric of λ_1 under area preserving deformations. For this, we set $\varphi_0 = \sqrt{1 - \varphi_1^2 - \varphi_2^2}$ and define the map $h : \mathbb{K} \rightarrow \mathbb{S}^4$ by $h = (\varphi_0(y), \varphi_1(y)e^{ix}, \varphi_2(y)e^{2ix})$. It suffices to check that the components of h are first eigenfunctions of Δ_g satisfying (4).

Indeed, in the next section we will see that the second order differential system satisfied by φ_1 and φ_2 (Condition (a)) admits the two following first integrals:

$$(6) \quad \begin{cases} (\varphi_1^2 + 4\varphi_2^2)^2 - \varphi_1^2 - 16\varphi_2^2 + \varphi_1'^2 + 4\varphi_2'^2 = C, \\ 12\varphi_2^2(\varphi_2^2 - 1) + 3\varphi_1^2\varphi_2^2 + \varphi_2^2\varphi_1'^2 - 2\varphi_1\varphi_1'\varphi_2\varphi_2' + (3 + \varphi_1^2)\varphi_2'^2 = C, \end{cases}$$

with $C = 4\varphi_2(0)^2(4\varphi_2(0)^2 - 3)$ (note that Condition (b) implies that $\varphi_1(0) = \varphi_2'(0) = 0$). Differentiating $\varphi_0^2 + \varphi_1^2 + \varphi_2^2 = 1$ and using the second equation in (6), we get

$$\begin{aligned} \varphi_0^2\varphi_0'^2 &= \varphi_1^2\varphi_1'^2 + \varphi_2^2\varphi_2'^2 + 2\varphi_1\varphi_1'\varphi_2\varphi_2' \\ &= \varphi_1^2\varphi_1'^2 + \varphi_2^2\varphi_2'^2 + 12\varphi_2^2(\varphi_2^2 - 1) + 3\varphi_1^2\varphi_2^2 + \varphi_2^2\varphi_1'^2 + (3 + \varphi_1^2)\varphi_2'^2 - C \\ &= (\varphi_1^2 + \varphi_2^2)\varphi_1'^2 + (3 + \varphi_1^2 + \varphi_2^2)\varphi_2'^2 + 12\varphi_2^2(\varphi_2^2 - 1) + 3\varphi_1^2\varphi_2^2 - C \\ &= (1 - \varphi_0^2)\varphi_1'^2 + (4 - \varphi_0^2)\varphi_2'^2 + 12\varphi_2^2(\varphi_2^2 - 1) + 3\varphi_1^2\varphi_2^2 - C. \end{aligned}$$

Therefore

$$\begin{aligned} \varphi_0^2(\varphi_0'^2 + \varphi_1'^2 + \varphi_2'^2) &= \varphi_1'^2 + 4\varphi_2'^2 + 12\varphi_2^2(\varphi_2^2 - 1) + 3\varphi_1^2\varphi_2^2 - C \\ &= (1 - \varphi_1^2 - \varphi_2^2)(\varphi_1^2 + 4\varphi_2^2), \end{aligned}$$

where the last equality follows from the first equation of (6). Hence,

$$|\partial_y h|^2 = \varphi_0'^2 + \varphi_1'^2 + \varphi_2'^2 = \varphi_1^2 + 4\varphi_2^2 = |\partial_x h|^2$$

and, since $\partial_x h$ and $\partial_y h$ are orthogonal, the map h is isometric, which means that Equation (4) is satisfied.

From Condition (a) one has $\varphi_1'' = (1 - 2f)\varphi_1$ and $\varphi_2'' = (4 - 2f)\varphi_2$, which implies that the functions $h_1 = \varphi_1(y) \cos x$, $h_2 = \varphi_1(y) \sin x$, $h_3 = \varphi_2(y) \cos 2x$ and $h_4 = \varphi_2(y) \sin 2x$ are eigenfunctions of Δ_g associated with the eigenvalue $\lambda = 2$. Moreover, differentiating twice the identity $\varphi_0^2 + \varphi_1^2 + \varphi_2^2 = 1$ and using Condition (a) and the identity $\varphi_0'^2 + \varphi_1'^2 + \varphi_2'^2 = \varphi_1^2 + 4\varphi_2^2 = f$, one obtains after an elementary computation, $\varphi_0'' = -2f\varphi_0$. Hence, all the components of h are eigenfunctions of Δ_g associated with the eigenvalue $\lambda = 2$. It remains to prove that 2 is the first positive eigenvalue of Δ_g or, equivalently, for each $k = 0, 1, 2$, the function φ_k corresponds to the lowest positive eigenvalue of the Sturm-Liouville problem $\varphi'' = (k^2 - \lambda f)\varphi$ subject to the parity condition $\varphi(-y) = (-1)^k \varphi(y)$. As explained in the proof of Proposition 3.4.1 of [12], this follows from conditions (c) and (d) giving the number of zeros of φ_k , and the special properties of the zero sets of solutions of Sturm-Liouville equations (oscillation theorems of Haupt and Sturm). \square

3. STUDY OF THE DYNAMICAL SYSTEM: PROOF OF RESULTS

According to Proposition 2.1, one needs to deal with the following system of second order differential equations (Condition (a) of Prop. 2.1)

$$(7) \quad \begin{cases} \varphi_1'' = (1 - 2\varphi_1^2 - 8\varphi_2^2)\varphi_1, \\ \varphi_2'' = (4 - 2\varphi_1^2 - 8\varphi_2^2)\varphi_2, \end{cases}$$

subject to the initial conditions (Condition (b) of Prop. 2.1)

$$(8) \quad \begin{cases} \varphi_1(0) = 0, & \varphi_2(0) = p, \\ \varphi_1'(0) = 2p, & \varphi_2'(0) = 0, \end{cases}$$

where $p \in (0, 1]$ (Condition (d) of Prop. 2.1).

Notice that the system (7)-(8) is invariant under the transform

$$(\varphi_1(y), \varphi_2(y)) \mapsto (-\varphi_1(-y), \varphi_2(-y)).$$

Consequently, the solution (φ_1, φ_2) of (7)-(8) is such that φ_1 is odd and φ_2 is even.

We are looking for periodic solutions satisfying the following condition (Condition (c) of Prop. 2.1):

$$(9) \quad \begin{cases} \varphi_1 \text{ has exactly two zeros in a period,} \\ \varphi_2 \text{ is positive everywhere.} \end{cases}$$

Our aim is to prove the following

Theorem 3.1. *There exists only one periodic solution of (7)-(8) satisfying Condition (9). It corresponds to the initial value $\varphi_2(0) = p = \sqrt{3/8}$.*

In fact, this theorem follows from the qualitative behavior of solutions, in terms of p , given in the following

Proposition 3.1. *Let (φ_1, φ_2) be the solution of (7)-(8).*

- (1) *For all $p \in (0, 1]$, $p \neq \sqrt{3}/2$, (φ_1, φ_2) is periodic or quasi-periodic.*
- (2) *For $p = \frac{\sqrt{3}}{2}$, (φ_1, φ_2) tends to the origin as $y \rightarrow \infty$ (hence, it is not periodic).*
- (3) *For all $p \in (\sqrt{3}/2, 1]$, φ_2 vanishes at least once in each period (of φ_2). Hence, Condition (9) is not satisfied.*
- (4) *There exists a countable dense subset $\mathcal{P} \subset (0, \sqrt{3}/2)$, with $\sqrt{3/8} \in \mathcal{P}$, such that the solution (φ_1, φ_2) corresponding to $p \in (0, \sqrt{3}/2)$ is periodic if and only if $p \in \mathcal{P}$.*
- (5) *For $p = \sqrt{3/8}$, (φ_1, φ_2) satisfies (9) and, for any $p \in \mathcal{P}$, $p \neq \sqrt{3/8}$, φ_1 admits at least 6 zeros in a period.*

The first fundamental step in the study of the system above is the existence of the following two independent first integrals.

3.1. First integrals. The functions

$$(10) \quad \begin{cases} H_1(\varphi_1, \varphi_2, \varphi_1', \varphi_2') := (\varphi_1^2 + 4\varphi_2^2)^2 - \varphi_1^2 - 16\varphi_2^2 + (\varphi_1')^2 + 4(\varphi_2')^2, \\ H_2(\varphi_1, \varphi_2, \varphi_1', \varphi_2') := 12\varphi_2^2(\varphi_2^2 - 1) + 3\varphi_1^2\varphi_2^2 + \varphi_2^2(\varphi_1')^2 \\ \qquad \qquad \qquad - 2\varphi_1\varphi_1'\varphi_2\varphi_2' + (3 + \varphi_1^2)(\varphi_2')^2, \end{cases}$$

F is a polynomial of degree ≤ 4 . Apart the three quadrics above, the only additional solution of this type we found is

$$w_4 = (\varphi_1^2 + 4\varphi_2^2)^2 - 12\varphi_2^2 = 0.$$

Like $(w_1 = 0)$, the curve $(w_4 = 0)$ is independent of p and represents the orbit of a particular solution of (12) for arbitrary values of p . Since

$$w_4(\varphi_1, \varphi_2) = (\varphi_1^2 + 4\varphi_2^2 - 2\sqrt{3}\varphi_2)(\varphi_1^2 + 4\varphi_2^2 + 2\sqrt{3}\varphi_2),$$

the set $(w_4 = 0)$ is the union of two ellipses passing through the origin, each one being symmetric to the other with respect to the φ_1 -axis. The upper ellipse

$$(15) \quad \varphi_1^2 + 4\varphi_2^2 - 2\sqrt{3}\varphi_2 = 0$$

corresponds to the orbit of the solution of (12)-(13) associated with $p = \frac{\sqrt{3}}{2}$.

3.3. Proof of Proposition 3.1(2): case $p = \frac{\sqrt{3}}{2}$. In this case, the orbit of the solution of (12)-(13) is given by (15). The only critical point of (12) lying on this ellipse is the origin, which is also a critical point of the system (7). Therefore, $(\varphi_1(y), \varphi_2(y))$ tends to the origin as y goes to infinity, and, hence, it is not periodic (see also [12]).

From now on, we will assume that $p \neq \frac{\sqrt{3}}{2}$.

3.4. A bounded region for the orbit. The orbit of the solution of (12)-(13) must lie in the region of the (φ_1, φ_2) -plane where the discriminant Δ of (14) is nonnegative. This region, $(\Delta \geq 0)$, is a bounded domain delimited by the unit circle $(w_1 = 0)$ and the quadrics $(w_2 = 0)$ and $(w_3 = 0)$. Its shape depends on the values of p .

- For $p \in (0, \sqrt{3}/2)$, $(w_2 = 0)$ and $(w_3 = 0)$ are hyperbolae.
- The case $p = \sqrt{3}/8$ is a special one since then, $w_3 \equiv -4w_2$, and the region $(\Delta \geq 0)$ shrinks to the arc of the hyperbola $(w_2 = 0)$ lying inside the unit disk.
- For $p \in (\sqrt{3}/2, 1]$, w_3 is positive and $(w_2 = 0)$ is an ellipse.

From (14) and (12) one can express φ_1' and φ_2' in terms of φ_1 , φ_2 and p . Thus, we obtain a multi-valued 2-dimensional dynamical system parameterized by p with the initial conditions $\varphi_1(0) = 0$ and $\varphi_2(0) = p$. However, the dynamics of such a multi-valued system is very complex to study. Fortunately, as we will see in the next subsections, the system (7) can be transformed, by means of a suitable change of variables, into a Hamiltonian system, completely integrable by quadratures.

3.5. Hamiltonian dynamical system. Let us introduce the new variables q_1 and q_2 defined by

$$(16) \quad q_1 := \frac{1}{\sqrt{2}}\varphi_1 \quad , \quad q_2 := \sqrt{2}\varphi_2.$$

The system (7) becomes

$$(17) \quad \begin{cases} q_1'' = [1 - 4(q_1^2 + q_2^2)]q_1 = -\frac{\partial V}{\partial q_1}, \\ q_2'' = 4[1 - q_1^2 - q_2^2]q_2 = -\frac{\partial V}{\partial q_2}, \end{cases}$$

Observe that the system (20) is symmetric in u and v . As the change of variables (19) is also symmetric in u and v , and since uv must be non positive, one can assume, without loss of generality, that $u \geq 0$ and, hence, $-\frac{3}{2} \leq v \leq 0$. Now, the condition ($\Delta \geq 0$) implies that $(u, v) \in I_1 \times I_2$, where

$$(21) \quad I_1 := [\alpha_0, 1/2] := \begin{cases} [0, \frac{1}{2}] & \text{if } p^2 < \frac{3}{4}, \\ [2p^2 - \frac{3}{2}, \frac{1}{2}] & \text{if } \frac{3}{4} < p^2 \leq 1, \end{cases}$$

and

$$(22) \quad I_2 := [a_0, a_1] := \begin{cases} [2p^2 - \frac{3}{2}, -2p^2] & \text{if } p^2 \leq \frac{3}{8}, \\ [-2p^2, 2p^2 - \frac{3}{2}] & \text{if } \frac{3}{8} \leq p^2 < \frac{3}{4}, \\ [-\frac{3}{2}, 0] & \text{for } \frac{3}{4} < p^2 \leq 1. \end{cases}$$

The initial conditions (13) become

$$(u(0), v(0)) = \begin{cases} (0, 2p^2 - \frac{3}{2}) & \text{if } p^2 < \frac{3}{4}, \\ (2p^2 - \frac{3}{2}, 0) & \text{if } \frac{3}{4} < p^2 \leq 1. \end{cases}$$

In all cases, $u(0)$ and $v(0)$ are zeros of P . Hence

$$(u'(0), v'(0)) = (0, 0).$$

The behavior of (u, v) near $y = 0$ is then determined by the acceleration vector

$$(u''(0), v''(0)) = \begin{cases} (\frac{12p^2}{3-4p^2}, \frac{16p^2(1-p^2)(3-8p^2)}{(3-4p^2)}) & \text{if } p^2 < \frac{3}{4}, \\ (\frac{16p^2(1-p^2)(3-8p^2)}{(3-4p^2)}, \frac{12p^2}{3-4p^2}) & \text{if } \frac{3}{4} < p^2 \leq 1. \end{cases}$$

Notice that for $p = \sqrt{\frac{3}{8}}$, v is constant, namely $v(y) = -\frac{3}{4}$ for all y , while for $p = 1$, u is constant with $u(y) = \frac{1}{2}$ for all y .

3.6. Proof of Proposition 3.1(1): Decoupling the system. In order to completely decouple the previous system we introduce a change of the independent variable $y \mapsto \tau$ defined by:

$$\frac{d\tau}{dy} = \frac{1}{u-v}.$$

Notice that this change of variable is one-to-one since $u - v \neq 0$ (indeed, $I_1 \cap I_2 = \emptyset$). In this new variable, the system splits into two independent equations:

$$(23) \quad (\dot{u})^2 = P(u),$$

$$(24) \quad (\dot{v})^2 = P(v),$$

where $\dot{u} := du/d\tau$ and $\dot{v} := dv/d\tau$. The solution $\tau \mapsto u(\tau)$ of (23) is also a solution of the second order ODE

$$(25) \quad \ddot{u} = \frac{1}{2}P'(u),$$

with the initial conditions $u(0) = \alpha_0$ (see (21) for the definition of α_0) and $\dot{u}(0) = 0$, where $P' := dP/du$. This solution lies on the curve

$$(26) \quad (\dot{u})^2 - P(u) = 0$$

in the (u, \dot{u}) -phase plane of (25). Since α_0 and $\frac{1}{2}$ are two consecutive zeros of P , the equation (26) in the region $\alpha_0 \leq u \leq \frac{1}{2}$ represents a closed curve. On the other hand, it is easy to check that P and P' admit no common zero in the interval $[\alpha_0, \frac{1}{2}]$. Hence, there exists no critical point for (25) on the orbit defined by (26) inside the region $\alpha_0 \leq u \leq \frac{1}{2}$. Consequently, this closed orbit corresponds to a periodic solution of (25) and, therefore, $\tau \mapsto u(\tau)$ oscillates between α_0 and $\frac{1}{2}$.

A similar analysis for $\tau \mapsto v(\tau)$ implies that it is a periodic solution of

$$(27) \quad \ddot{v} = \frac{1}{2}P'(v),$$

with the initial conditions $v(0) = a_0$ (see (22) for the definition of a_0) and $\dot{v}(0) = 0$. Consequently, $\tau \mapsto v(\tau)$ oscillates between a_0 and a_1 . This proves Assertion (1) of Proposition 3.1(1).

3.7. Proof of Proposition 3.1(3): case $p > \frac{\sqrt{3}}{2}$. We have just seen that $v(\mathbb{R}) = [a_0, a_1]$, with $a_0 = -\frac{3}{2}$ for $p \in (\frac{\sqrt{3}}{2}, 1]$ (see (22)). This implies that q_2 , and then φ_2 , vanishes at least once in a period (see (19)).

3.8. About the periods of u and v : case $p < \frac{\sqrt{3}}{2}$. Let us denote $\mathcal{T}_u(p)$ the period of u . The function $\tau \mapsto u(\tau)$ oscillates between $\alpha_0 = 0$ and $\frac{1}{2}$ with velocity $(\dot{u})^2 = P(u) \neq 0$ if $u \in (0, \frac{1}{2})$. Hence, $u(\tau)$ increases from 0 to $\frac{1}{2}$ when τ goes from 0 to $\frac{\mathcal{T}_u(p)}{2}$. It follows that

$$(28) \quad \mathcal{T}_u(p) = 2 \int_0^{\frac{1}{2}} \frac{ds}{\sqrt{P(s)}}.$$

Similarly, for $p \neq \sqrt{3/8}$, the period $\mathcal{T}_v(p)$ of $\tau \mapsto v(\tau)$ is given by

$$\mathcal{T}_v(p) = 2 \int_{a_0}^{a_1} \frac{ds}{\sqrt{P(s)}}.$$

Setting, for $p \neq \sqrt{3/8}$, $s = (3 - 8p^2)r - \frac{3}{2} + 2p^2$, one can write

$$(29) \quad \mathcal{T}_v(p) = 2 \int_0^{\frac{1}{2}} \frac{dr}{\sqrt{Q(r)}},$$

where

$$Q(r) := 2r(1-2r)[2p^2 + (3-8p^2)r][2-2p^2 - (3-8p^2)r][3-4p^2 - 2(3-8p^2)r].$$

Hence, the functions $\mathcal{T}_u(p)$ and $\mathcal{T}_v(p)$ are explicitly given by complete hyperelliptic integrals. Although the function \mathcal{T}_v is not defined at $p = \sqrt{3/8}$, its limit exists. Indeed, setting $t = \frac{3}{4} + r$ and $\alpha := \frac{3}{4} - 2p^2$, we get

$$\mathcal{T}_v(p) = 2 \int_{-\alpha}^{\alpha} \frac{dt}{\sqrt{(\frac{3}{2} - 2t)(\frac{5}{2} - 2t)(\frac{3}{2} + 2t)\sqrt{\alpha^2 - t^2}}}.$$

As $\alpha \rightarrow 0$, we have

$$\mathcal{T}_v(p) \sim 2 \int_{-\alpha}^{\alpha} \frac{4dt}{3\sqrt{10}\sqrt{\alpha^2 - t^2}}.$$

Thus

$$\lim_{p \rightarrow \sqrt{\frac{3}{8}}} \mathcal{T}_v(p) = \frac{8\pi}{3\sqrt{10}}.$$

On the other hand, we have

$$\mathcal{T}_u(\sqrt{3/8}) = \frac{4}{5}\Pi(2/5, 1/4),$$

where Π is the complete elliptic integral of the third kind given by

$$\Pi(n, m) := \int_0^{\frac{\pi}{2}} \frac{d\theta}{(1 - n \sin^2 \theta)\sqrt{1 - m \sin^2 \theta}}.$$

Since for $p = \sqrt{3/8}$, v is constant, the couple (u, v) is periodic of period $\mathcal{T}_u(\sqrt{3/8})$.

Behavior of $\mathcal{T}_v - \mathcal{T}_u$ and $\mathcal{T}_v/\mathcal{T}_u$ near $p = 0$: One has

$$\mathcal{T}_v(p) - \mathcal{T}_u(p) = 2 \int_0^{\frac{1}{2}} \left[\frac{1}{\sqrt{Q(s)}} - \frac{1}{\sqrt{P(s)}} \right] ds.$$

The integral of $\frac{1}{\sqrt{P(s)}}$ is singular only at $p = 0$. A direct computation gives

$$\int_0^{\frac{1}{2}} \frac{ds}{\sqrt{P(s)}} \sim \int_0^{\frac{1}{2}} \frac{ds}{3\sqrt{s^2 + 2p^2s}} \sim -\frac{2}{3} \ln(p).$$

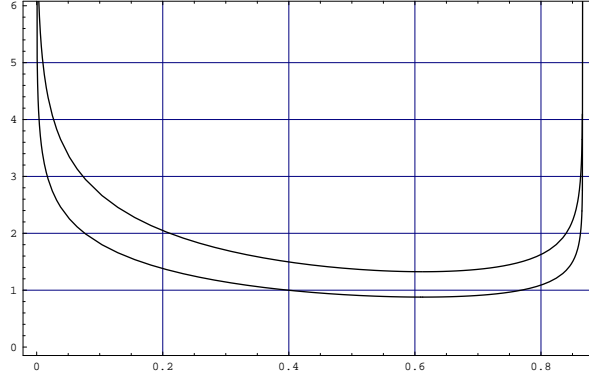
Similarly, we get

$$\int_0^{\frac{1}{2}} \frac{ds}{\sqrt{Q(s)}} \sim -\ln p.$$

In other words $\mathcal{T}_v(p) - \mathcal{T}_u(p) \rightarrow +\infty$ as $p \rightarrow 0$ while the ratio $\mathcal{T}_v(p)/\mathcal{T}_u(p)$ goes to $\frac{3}{2}$ (see the figure below).

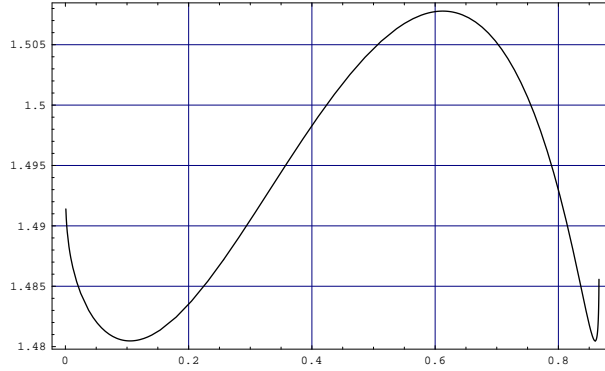
Behavior of $\mathcal{T}_v - \mathcal{T}_u$ and $\mathcal{T}_v/\mathcal{T}_u$ near $p = \sqrt{3}/2$: As $p \rightarrow \sqrt{3}/2$, $\mathcal{T}_u(p) \sim -\frac{2}{3} \ln(\sqrt{3}/2 - p)$ and $\mathcal{T}_v(p) \sim -\ln(\sqrt{3}/2 - p)$. Hence, $\mathcal{T}_v - \mathcal{T}_u \rightarrow +\infty$ as $p \rightarrow \sqrt{3}/2$ and $\mathcal{T}_v(p)/\mathcal{T}_u(p)$ goes again to $\frac{3}{2}$.

Thus, $\mathcal{T}_v(p) > \mathcal{T}_u(p)$ near $p = 0$ and $p = \sqrt{3}/2$. Actually, one has $\mathcal{T}_v(p) > \mathcal{T}_u(p)$ for all $p \in (0, \sqrt{3}/2)$ as shown by the graphic representation of \mathcal{T}_v and \mathcal{T}_u given below.



The functions $p \mapsto \mathcal{T}_v(p)$ (the upper one) and $p \mapsto \mathcal{T}_u(p)$.

3.9. Proof of Proposition 3.1(4). The couple (u, v) is periodic if and only if the ratio $R(p) := \frac{\mathcal{T}_v(p)}{\mathcal{T}_u(p)}$ is a rational number. From the previous subsection, R is a nonconstant continuous function on $(0, \sqrt{3}/2)$ with $\lim_{p \rightarrow 0} R(p) = \lim_{p \rightarrow \sqrt{3}/2} R(p) = 3/2$. The range of R is a closed interval $[r_1, r_2] \subset [1.480473, 1.507784]$ (see the figure below).



The ratio $\frac{\mathcal{T}_v}{\mathcal{T}_u}$

To end the proof of Assertion (4), we only need to define \mathcal{P} to be the set of $p \in (0, \sqrt{3}/2)$ such that $R(p)$ is a rational number.

3.10. Proof of Proposition 3.1(5). In the case $p = \sqrt{3}/8$ we have, $\forall y \in \mathbb{R}$, $v(y) = -\frac{3}{4}$ and, then, $\varphi_1^2 = u$ and $\varphi_2^2 = \frac{1}{8}(3 + 2u)$. The couple of periodic functions $(\varphi_1, \varphi_2) = (\sqrt{u}, \sqrt{\frac{1}{8}(3 + 2u)})$ on $[0, \mathcal{T}_u(\sqrt{3}/8)]$, such that φ_1 is odd and φ_2 is even, solves the original system and satisfies Condition (9).

Let $p \in \mathcal{P}$, $p \neq \sqrt{3}/8$, and let $\frac{q}{m} \in \mathbb{Q}$ be an irreducible fraction, with $q, m \in \mathbb{N}$, such that $R(p) = \frac{\mathcal{T}_v(p)}{\mathcal{T}_u(p)} = \frac{q}{m}$. The period of the couple (u, v) is given by

$$\mathcal{T}(p) = q\mathcal{T}_u(p) = m\mathcal{T}_v(p).$$

The number of zeros of u in a period, for instance $[0, \mathcal{T}(p))$, of (u, v) is equal to q times the number of zeros of u in $[0, \mathcal{T}_u(p))$. As we saw above, $\forall p \in (0, \sqrt{3}/2)$, one has $1 < R(p) < 2$. Hence, $m \geq 2$ and $q > m$, which implies $q \geq 3$. Since $u(0) = 0$, the number of zeros of u in a period of (u, v) is at least 3. Since φ_1 is odd, the period of (φ_1, φ_2) is twice the period

of (u, v) . From $\varphi_1 = 2\sqrt{-\frac{1}{3}uv}$ on $[0, \mathcal{T}(p))$, one deduces that φ_1 admits at least 6 zeros in a period of (φ_1, φ_2) . Notice that the case $p = \sqrt{3/8}$ is special since, for this value of p , v is constant and the couple (u, v) is periodic whose period is equal to that of u .

3.11. On the shape of solutions. Although it is not necessary for the proof of our main result, one can obtain as a by product of our study, some properties concerning the shape of solutions. First, notice that, for $p \in (0, \frac{\sqrt{3}}{2})$, the 2-dimensional dynamical system admits four critical points in the region $(\Delta \geq 0) \cap (\varphi_2 \geq 0)$: $A = (2p/\sqrt{3}, \sqrt{1-4p^2/3})$, $B = (\sqrt{1-4p^2/3}, 2p/\sqrt{3})$ and their symmetric with respect to the φ_2 -axis that we denote A' and B' . Notice that these critical points are on the boundary of the region $(\Delta \geq 0)$. Non-periodic solutions. They correspond to the case where $\mathcal{T}_v(p)/\mathcal{T}_u(p)$ is irrational. In this case, the orbit (u, v) fill the rectangle $I_1 \times I_2$, and, then, in the (φ_1, φ_2) -plane, the orbit fill the region $(\Delta \geq 0)$.

Periodic solutions. For $p = \sqrt{3/8}$, the solution (φ_1, φ_2) lies on the hyperbola of equation $\varphi_1^2 - 4\varphi_2^2 + 3/2 = 0$, oscillating between the points $A = (-\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}})$ and $A' = (\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}})$. For $p \neq \sqrt{3/8}$, let $q/m = \mathcal{T}_v(p)/\mathcal{T}_u(p)$ be an irreducible fraction, with $q, m \in \mathbb{N}$, and set $\mathcal{T} := q\mathcal{T}_u(p) = m\mathcal{T}_v(p)$. Geometrically, this means that u makes q round trips in a period while v makes m round trips. We distinguish three cases:

- If q and m are both odd, then $u(\mathcal{T}/2) = \frac{1}{2}$ and $v(\mathcal{T}/2) = a_1$. This corresponds to the point A for $p^2 < \frac{3}{8}$ and to the point B for $\frac{3}{8} < p^2 < \frac{3}{4}$. The orbit is not closed and (φ_1, φ_2) oscillates between A and A' or B and B' .
- If q is odd and m is even, then $u(\mathcal{T}/2) = \frac{1}{2}$ and $v(\mathcal{T}/2) = a_0$. This corresponds to the point B for $p^2 < \frac{3}{8}$ and to the point A for $\frac{3}{8} < p^2 < \frac{3}{4}$. Again, (φ_1, φ_2) oscillates between A and A' or B and B' .
- If q is even and m is odd, then $u(\mathcal{T}/2) = 0$ and $v(\mathcal{T}/2) = a_1$. This corresponds in the (φ_1, φ_2) -plane to the point $(0, \frac{3}{4} - p^2)$. This point is the intersection between the quadric $(w_3 = 0)$ with the φ_2 -axis. In this case the orbit is closed.

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